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ALIAGES: A SYSTEM FOR THE ASSIGNMENT
OF BUS ROUTES TO GARAGES

by

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ABSTRACT

The objective of the system described is to assign vehicle trips independently or by lines to the various garages of a transit company in order to minimize both the number of vehicles required and the deadhead costs. The system can also be used to study the optimal location of new garages.

A heuristic procedure is proposed for solving this problem because of the variety of operational constraints which must be respected. These constraints include the requirement for trips of a subset of routes to be assigned to a specific garage, to only one garage among a given subset, or to be split amongst no more than two or three garages.

Constraints on the minimum and maximum number of buses assigned to a garage for peak and off-peak services are also imposed.

The problem and solution methods are discussed in the context of the S.T.C.U.M., (the Montreal Transit Commission) where the system will be implemented.

Key words: transit, vehicle scheduling, multiple garages.

RÉSUMÉ

Aliage est un système informatique qui permet l'allocation des tournées de véhicules aux multiples garages d'une compagnie de transport en commun. Le système permet également de calculer l'affectation et l'horaire des véhicules de chaque garage. Plusieurs contraintes opérationnelles nous empêchent d'utiliser des méthodes de solutions optimales. Le rapport présente donc une méthode approximative de solution. Le problème est discuté dans le contexte de l'exploitation de la S.T.C.U.M.

Mots-clés : transport en commun, affectation de véhicules, garages multiples.

Introduction

Most large transit companies operate several garages, and must face the problem of deciding which garages will adequately serve bus routes. Several costs and operational constraints must be taken into account in the decision process. Since terminology varies between transit operators, we first define some basic terms.

A bus route is the basic element of a transit service. It is described by a fixed itinerary and has a unique identifier. A trip is performed by a bus running from one terminal of a bus route to another. A block is an indivisible element of the vehicle scheduling problem. It is composed of one or several trips normally carried out on a single bus route. In the vehicle scheduling problem, blocks cannot be split into several parts. A combined block is a set of blocks that can be performed by the same vehicle. The formation of combined blocks is normally part of the vehicle scheduling problem.

The Problem

Suppose that a transit company has several garages, each characterized by a particular location on the territory and by a specific capacity. Blocks and combined blocks of vehicles must be assigned to each garage in order to minimize operational costs which are, in this case, the fixed cost of operating the vehicles, the deadhead cost (both for crew and vehicles) incurred by operating each combined block out of this location, and garage operating costs related to the arrival and departure of vehicles. For example, all vehicles must return to their home garage every day for maintenance purposes. Several other operational constraints must also be respected.

As part of the operational constraints, the company might impose that each garage be used at a minimum percentage of its capacity even if it is not cost efficient. For example, the more recent garages may be located

in industrial parks rather than residential areas and impose on the companies greater operating costs related to deadheading and crew travel costs. These garages, however, may be more effective for bus maintenance activity or they may simply be used at high levels for political reasons. Also during the working hours of the mechanics, a certain minimum number of buses must always be out of the garage to facilitate the maintenance and movement of other buses within the garage.

Moreover, for control reasons, the company will generally prefer that all blocks related to a bus route be allocated to a single garage or if not, to two or three garages at the most. There might also be traditional reasons for allocating buses of certain bus routes to some specific garage.

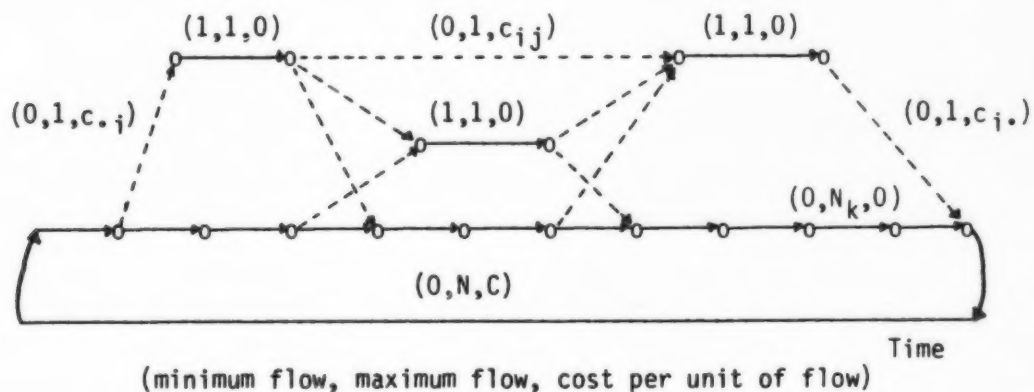
These latter operational constraints require a flexible decision process which allows the user to prespecify certain assignments of blocks to garages.

Considering the cost structure of this problem, it is clear that the assignment of blocks to garages is interrelated with the vehicle scheduling problem. In fact, to minimize the number of buses necessary to operate a schedule, we may consider the problem of allocating the blocks to a minimum number of vehicles. The results, however, may generate high deadhead costs to and from the home garage. On the other hand, assigning blocks to garages first to minimize deadhead cost may result in using a greater number of buses than necessary. The trade-off between these two elements must be considered and may be different from one transit organization to another depending, for example, on the amount of subsidies for new buses, the availability of buses and the financing of operating deficits. However, because we wanted to consider explicitly all operational constraints, we were forced to choose the second alternative in which the blocks are first allocated to garages before the number of vehicles is minimized.

The Single Garage Problem

In order to achieve a better understanding of the multiple garage problem, we first define the single garage case which is a standard vehicle scheduling problem. This problem has been widely studied (see, for example, Scott (1986), Rousseau (1986), for an overview). We present here the approach used by Desrosiers et al. (1982).

Desrosiers et al. (1982) have presented a scheduling model which takes into account the use of a single vehicle to serve many blocks. Figure 1 describes the approach proposed. In this approach, each block in the schedule is represented by an arc with a minimal and maximal flow of one thus requiring a unit flow to traverse it. There is no specific cost associated with the trips themselves because they all have to be used. All feasible deadhead trips are also represented by arcs with a minimum flow of zero and maximum flow of one and an associated cost c_{ij} corresponding to the cost of deadhead time and distance. Equivalently, a cost is associated with travel to and from the garage ($c_{i,}$, $c_{,i}$). The originality of this



- o—o : correspond to trips
 - - - : deadhead trip to or from the depot or between regular trips

Figure 1 : A time space network for the transit bus scheduling problem.

formulation lies in the fact that the garage is not represented by a single node but by a sequence of time nodes. All buses in the garage can flow freely from one time node to the next time node without cost. A bound N_k on the maximum number of buses in the garage at time period k can be easily imposed on the solution. Finally a return arc from the end of the day to the beginning of the day ensures the conservation of flow and counts the number of buses required to operate the schedule. The fixed cost C of a vehicle and an upper bound N on the number of vehicles can be imposed on this arc.

A standard minimum cost flow algorithm can be used to solve this problem. This formulation accurately takes into account the number of buses required without generating too many arcs.

However, it is important to note that Scott (1986) has demonstrated recently that if deadhead cost is proportional to travel time and waiting time, which are characteristic of a broad class of vehicle scheduling problems, there need not be any conflict between the two objectives of minimizing fleet size and minimizing the cost of operating a schedule. In other words, there is never, in general, any need for the application of a fleet size penalty to the creation of independent chains when one intends to find a minimum-cost scheduling solution which uses a minimal fleet.

The Multiple Garage Problem

The problem is presented here as the integrated problem of assigning blocks to garages and scheduling vehicles for single garage operation. We first define:

Sets : $V = \{v_1, \dots, v_n\}$ is the set of blocks;

$V_\ell \subset V; \cup V_\ell = V$ is a partition of V . For example, V_ℓ can be the set of blocks belonging to a route or a set of routes. It can also be a single block. Specific constraints will apply to these sets; $\ell=1, \dots, L$.

G_i is the subset of garages to which block v_i can be assigned; an element of this subset will be called an admissible garage for block i ;

$B_k \subset V \quad k=1, \dots, K$ other subsets of V ;

Variables: $y_i^{(h)} = \begin{cases} 1 & \text{if block } i \text{ is assigned to garage } h \\ 0 & \text{otherwise;} \end{cases}$

$z_\ell^{(h)} = \begin{cases} 1 & \text{if some blocks of } V_\ell \text{ are assigned to garage } h \\ 0 & \text{otherwise.} \end{cases}$

There are H garages. The multiple garage problem (MGP) can now be formulated as follows:

Objective function:

$$\text{Min } \sum_h (\text{cost of vehicle schedule within garage } h)$$

Constraints on the assignment of blocks to garages

i) each block must be assigned to a garage:

$$\sum_{h \in G_i} y_i^{(h)} = 1, \quad i=1, \dots, n;$$

ii) the subset V_ℓ of blocks may not be split between more than P_ℓ garages:

$$\sum_{i \in V_\ell} y_i^{(h)} - M z_\ell^h < 0, \quad \ell=1, \dots, L$$

$$\sum_h z_\ell^h < P_\ell;$$

iii) a maximum number of blocks of a certain type (e.g. small blocks) may be assigned to a given garage h . A capacity constraint on the garage is imposed through one of these constraints:

$$\sum_{i \in B_k} y_i^{(h)} < q_k^{(h)}, \quad \text{for } k=1, \dots, K_1;$$

- iv) a minimum number of blocks of a certain type (e.g. long blocks) must be assigned to a given garage h ,

$$\sum_{i \in B_k} y_i^{(h)} > q_k^{(h)}, \quad \text{for } k=k_1+1, \dots, K;$$

- v) $y_i^{(h)}$ and $z_\ell^{(h)}$ are binary variables;

- vi) H independent single garage scheduling problems:



For the S.T.C.U.M. (Montreal) this formulation would result in more than 20,000 variables and 4,000 constraints.

Solution Approaches

This problem has been studied by several authors including Maze et al. (1985), Carraresi and Gallo (1984), Bodin et al. (1983), and Mandl (1980). Maze et al., as well as Mandl, use an integer programming formulation, similar to the one presented here, for which they claim that the LP solution would yield an integer solution in the majority of cases. However, for any real size problem the solution time for the LP problem seems prohibitive, probably because of the high level of degeneracy. In addition, they do not include the restrictive constraints which stipulate that the blocks of a bus route must not be split between too many garages. Carraresi and Gallo also do not consider this latter type of constraint, but have

demonstrated that Lagrangean relaxation can be applied successfully to this type of problem.

We chose to use a heuristic approach that is better able to take into account the practical operational constraints encountered in real problems. We also needed a fast solution process that can be used in a context where several options could be studied rapidly. In fact our approach decomposes the problem into two parts:

- i) assignment of blocks to garages;
- ii) optimization of the vehicle schedule within each garage.

Since the approach for the second part is well known, we present only the first part.

The Blocks to Garages Assignment Problem (BGA)

Mathematically, the problem to be solved can be written as follows, using the same notation as previously.

Objective function:

$$\text{Min} \quad \sum_h \sum_i d_i^{(h)} y_i^{(h)} + \sum_k \sum_h \lambda_k^{(h)} (s_k^{(h)})^\alpha.$$

$s_k^{(h)}$ is the slack violation for the constraints iii) and iv) of the MGP problem (including capacity constraints);

$d_i^{(h)}$ cost of assigning block i to garage h (deadhead, pull in, pull out, etc.).

Hard constraints on the assignment of blocks to garages:

- i) each block must be assigned to a garage:

$$\sum_{h \in G_i} y_i^{(h)} = 1, \quad i=1, \dots, n;$$

ii) the subset V_ℓ of blocks may not be split between more than P_ℓ garages:

$$\sum_{i \in V_\ell} y_i^{(h)} - Mz_\ell^{(h)} \leq 0, \quad \ell=1, \dots, L$$

$$\sum_h z_\ell^{(h)} \leq p_\ell.$$

iii) $y_i^{(h)}$ and $z_\ell^{(h)}$ are binary variables.

Note that in this formulation, all capacity constraints are considered (i.e. they are included in the objective function with a penalty factor). Also, constraint violations can be penalized more than linearly through an exponent α (e.g. $\alpha=2$). Our solution approach is heuristic in nature. Through a greedy constructive approach we generate a feasible solution to problem BGA. We then apply neighborhood search algorithms to improve the objective function. In most cases, this process will tend to generate a solution that respects all other soft constraints. If all soft constraints are not respected, the parameters λ and α may be increased and the search algorithm pursued. We now describe our approach in more detail.

Step 1: Create an initial solution by allocating each V_ℓ to one garage admissible for all blocks in V_ℓ . This is done by allocating V_ℓ to the garage h' where h' minimizes the deadhead cost of the assignment of its blocks to a garage.

$$\text{Min}_h \sum_{i \in V_\ell} d_i^{(h)}$$

This is a feasible solution to the problem (BGA).

Step 2: For each garage h select V_ℓ for which the best exchange procedure generates the best improvement in the objective function. Repeat Step 2 until no more exchanges are profitable.

Two such exchange procedures called opt-1 and opt-2 are available.

Procedure opt-1: For a given V_ℓ currently allocated to garage h , find the garage h' for which the allocation of V_ℓ to garage h' will generate the greatest reduction in the objective function of BGA. If $h \neq h'$, this becomes a candidate for exchange.

Procedure opt-2: For a given V_ℓ currently allocated to garage h find the garage h' , the set V_k currently allocated to h' and the garage h'' (could be h) for which the allocation of V_ℓ to h' and V_k to h'' will generate the greatest reduction in the objective function of BGA. If this reduction is positive, this becomes a candidate for exchange.

Step 3: If profitable, split in turn each V_ℓ among the maximum number (p_ℓ) of admissible garages.

This is done as follows:

First assign individual block i of V_ℓ to the admissible garage that will reduce most the objective function of BGA. This process might use more garages than the number of different garages allowed, p_ℓ .

If so, we exclude for V_ℓ the garage which generates the least increase in cost in BGA when made inadmissible. This is done until the maximum number of garages p_ℓ is attained.

Then individual blocks of V_ℓ are exchanged between admissible garages through the opt-1 and opt-2 procedures described previously until no more improvement in the objective function is possible.

The result is a new partition of V . Each subset of V_ℓ is now considered a new subset of V in replacement of V_ℓ .

Step 4: We perform Step 2 with the new partition resulting from Step 3.

Step 5: If all constraints are respected, we stop. Otherwise, we modify the λ 's and α 's in BGA and we may return to Step 4. If unsuccessful, we return to Step 1 with the new objective function.

The procedure is described in greater detail in Désilets and Lessard (1984).

Results and Utilisation

Several tests have been conducted on S.T.C.U.M. (Montreal) data and we were able to produce both feasible and acceptable solutions which generated cost savings.

However, the major impact of this system will probably be in the study of changes in the operations and planning policies. For example, all the operational restrictions on the allocation of blocks to garages, and limitations on sending the blocks of certain routes to certain garages may be studied to calculate their cost impact and eventually induce a change in policy. New garage location may also be studied with this system by carrying out evaluations of several scenarios of closing and/or opening garages. Also, the necessity of operating all the garages rather than only a few of them on weekends may be studied in more detail for cost impact.

The computer system provided allows the user to specify all restrictions as well as to specify assignments which are fixed in advance. In this context a multitude of operational scenarios can be studied normally leading to improved operational efficiency.

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